β in Streamers

S. T. Suess[a], G. A. Gary[a], and S. F. Nerney [b]

[a]*NASA Marshall Space Flight Center/ES82, Huntsville, Alabama 35812 and* [b]*Ohio University, 1570 Granville Pike, Lancaster, Ohio 43130*

Abstract. The ratio of thermal pressure to magnetic pressure (β) is greater than unity above $\sim 1.2\ R_S$ in streamers.

INTRODUCTION

Streamers are often described as regions of the corona in which the density is higher than in coronal holes because the plasma is trapped by closed loops of magnetic flux. Conversely, MHD models of the global corona (1) show that the plasma $\beta \equiv 8\pi p/B^2 > 1$ in streamers above $\sim 1.2 R_S$ heliocentric height (p=pressure, B=magnetic field strength). There are three recent contributions to the topic of the magnitude of β in streamers. The first is that heating near the cusp further drives β up and can result in release of new slow solar wind from the top of the streamer (2). The second is UVCS/SOHO observations, in combination with a potential field/source surface model of the magnetic field, show $\beta > 1$ above $1.2R_S$ in a streamer observed near solar sunspot minimum (3). The third is a magnetic field reconstruction technique (using field deforming algorithms) (4) which was applied both to an isolated active region (AR 7999) and to the Pneuman & Kopp (5)globalMHD model. In the active region, β becomes larger than unity at $\sim 1.2R_S$. In the Pneuman & Kopp model, $\beta = 1.0$ at the base of the streamer and riseswithincreasing height, becoming 15-20 at1 .6R_S and 35-55 at $1.7R_S$. The collective implication of these three results is that $\beta > 1$ in streamers above $\sim 1.2\ R_S$.

Global simulations go on to show that the reason streamers do not simply explode under such high β conditions is that they are held down by pressure exerted on the flanks of the streamers by the strong fields in adjacent coronal holes, where $\beta \ll 1$ (6). The main role of the closed magnetic loops near the cusp is to keep the steamer from continuously leaking plasma, as otherwise happens in a magnetic pinch which is similar but has no closed loops.

Accepting $\beta > 1$ to reflecttypicalconditionsinstreamers suggests consequences in the interpretation of other physical phenomena since β is a physically important parameter. For example, models of MHD wave heating often assume $\beta < 1$. In a $\beta > 1$ medium, Alfvén waves do not propagate efficiently and tend to convert to sound waves as they move into a $\beta > 1$ medium. As a second example, models of large loops in diffuse corona are often based on the assumption that $\beta < 1$ (7), using this as a basis for specifying the boundary condition at the tops of the loops. Instead, it is likely that isobars are surfaces at a constant height above 1.2 R_S. A third example is that analytic models for the pre-CME corona generally assume $\beta < 1$ (8), deducing the response of the corona to the CME only in that limit. Conversely, a better approximation may be to have CMEs start low in streamers and carry with them plasma from above 1.2 R_S where $\beta > 1$.

The purpose of this note is to summarize the results implying that $\beta > 1$ is a general property of streamers above 1.2 R_S.

GLOBAL MHD MODELS OF THE CORONA

Pneuman & Kopp's 1971 Model

The first global MHD model of the corona, by Pneuman and Kopp(5), was asolution to the steady stateequations for isothermal flow in the presence of a dipole magnetic field. Figure 1(a) shows field lines in this model, but neither the field strength nor β were published. To find the field strength we reproduced the field lines in the model by starting with a dipole potential field and deforming the field lines until they match those of Pneuman & Kopp. Gary & Alexander (4) developed a technique for contructing the coronal field by deforming an initial potential field while ensuring that: (i) the normal component of the photospheric field remaind unchanged and

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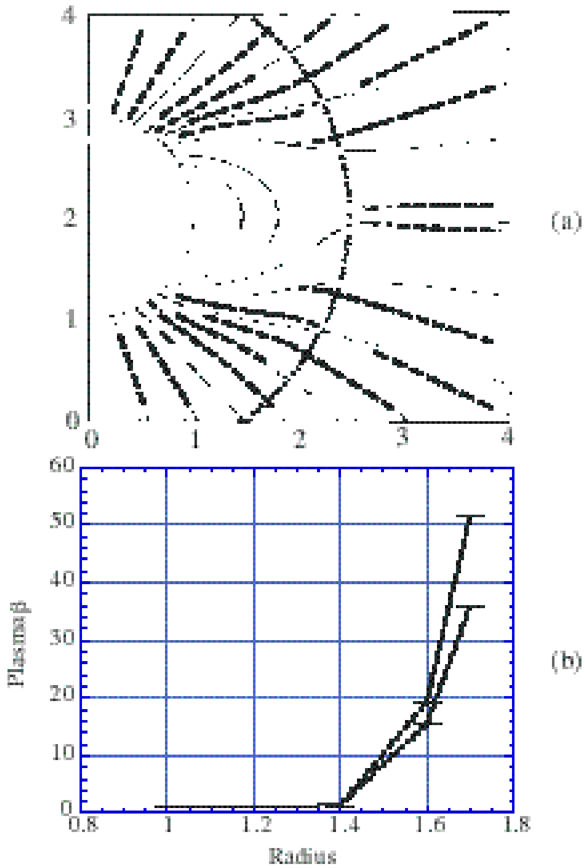

FIGURE 1. (a) Pneuman & Kopp's (5) exact MHD solution (solid lines) for global coronal flow and a dipole field. This is compared with a zero potential solution having a source surface at 2.492 R_S (dashed lines). (b) the plasma β along the axis of the streamer in the Pneuman & Kopp model.

(ii) the field remains divergence free. For a 2D field like Pnueman and Kopp's this method has no ambiguity.

Using the temperature and density directly from Pneuman & Kopp's paper and the field strength from Gary & Alexander's algorithm gives the values for β along the axis of the streamer that are shown in Figure 1(b). The Pneuman & Kopp model assumes $\beta = 1$ at the base and β increases slowly to $\beta = 1.4$ at 1.4 R_S. Figure 1(b) shows that above 1.4 R_S β increases rapidly and is already between 35 and 55 at 1.7 R_S. Naturally, $\beta \to \infty$ at the cusp, as is true in all streamer models, but the height of the streamer in this model is ~ 2.5 R_S so $\beta > 1$ throughout the bulk of the streamer.

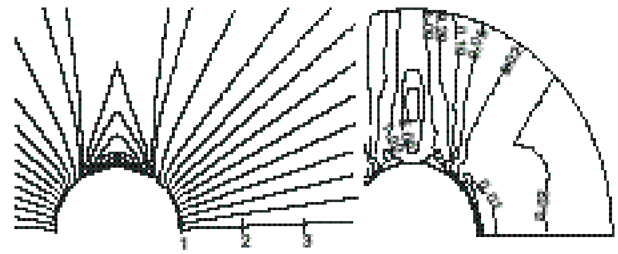

FIGURE 2. Field lines (left) and β contours (right) from a recent MHD coronal model that shows $\beta > 1$ throughout a streamer (9).

Modern Models

Typical numerical models of global coronal structure today begin with specified boundary values for the magnetic field and plasmavariables, a potentialmagnetic field in the corona, and spherical flow. The configuration then is allowed to relax in time untilit ischanging slowly compared to a coronal expansion time. A well-known early exampleof thistypemodelisthatofSteinolfsonetal. (1). That modelgave a reasonable result and $\beta > 1$ throughout the bulk of the streamer, much as in Pneuman & Kopp's model. However, the flow in the open field regions was a standard Parker wind with corresponding low flow speeds and high densities in comparison to whatis now known to exist in coronal holes. Models now generally incorporate heat and momentum source terms to produce reasonable coronal hole flow speeds and densities while retaining reasonable temperatures and densities in the streamers. Figure 2 illustrates one such model (9) which is typical in terms of the result that $\beta > 1$ throughout the body of the streamer while $\beta \ll 1$ in the coronal hole. The relatively strong coronal hole field pressing on the flanks of the streamer is again what provides the primary confining force for the streamer in this, and in similar models (6).

The assumption of a time-stationary heat source in the model shown in Figure 2 results in a slowly increasing temperature in the streamer. Field lines at the top of the streamer are consequently slowly forced open to release new slow solar wind in a process which has been called "streamer evaporation." Evaporation can occur only because $\beta > 1$ throughout the body ofthe streamer. Because the physics of streamer heating is not understood, the importance of evaporation is not known. Nevertheless, the tendency for model streamers to evaporate is indicative of the weak confinement of streamers by their internal magnetic field.

Table 1. Streamer Temperatures and Densities (3).

Height	1.15 R_S	1.5 R_S
Temperature	1.9×10^6 K	1.6×10^6 K
Density	1.15×10^8 cm^{-3}	1.26×10^6 cm^{-3}

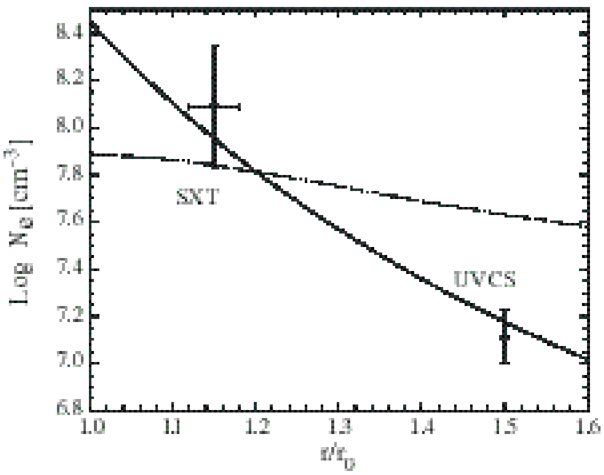

FIGURE 3. Density in streamers from (3), compared with a hydrostatic, isothermal equilibrium model (solid line) and the same model with thermal conduction (dashed line).

UVCS/SOHO AND SXT/YOHKOH STREAMER OBSERVATION

Estimating β empirically in streamers has always been a difficult problem because of the absence of direct measurements of the magnetic field in the corona. This problem still exists, but Li et al. (3) have attempted to minimize it by combining UVCS and SXT measurements of the plasma properties with a potential field model. They analyzed a coronal helmet streamer observed on 25 July 1996 and later found to be stable from 22 to 27 July. They derived temperatures and densities at 1.15 and 1.5 R_S with the results shown in Table 1. The electron density was compared with a hydrostatic, isothermal equilibrium model and a hydrostatic equilibrium plus thermal conduction model and it was concluded that the streamer is in hydrostatic equilibrium and isothermal within experimental uncertainty in the closed field regions. These comparisons are shown in Figure 3.

Li et al. estimated the magnetic field strength according to the potential field calculated by van Ballegooijen (see (10)). The extrapolation was based on NSO/Kitt Peak synoptic maps of the radial magnetic fields for the month of July 1996, along with the assumption of a source surface at 2.5 solar radii. The inferred field strength was 0.55 G at 1.15 R_S and 0.21 G at 1.5 R_S. The resulting plasma β is $\beta = 5$ at 1.15 R_S and $\beta = 3$ at 1.5 R_S. The conclusion was that gas pressure is important in the closed field region. This result is consistent with the MHD model results quoted above.

LARGE ACTIVE REGION LOOPS

As a final example of $\beta > 1$ in the corona, consider large active region loops which have commonly been characterized as $\beta < 1$ features (7). Gary & Alexander(4) analyzed SXT/YOHKOH filter ratio data from AR 7999, which crossed the Sun's central meridian on 26 November 1996. For the magnetic field they used line-of-sight photospheric magnetic field measurements. In this way, SXT gave temperatures and densities along bright loops, which were in turn modeled using the field deformation algorithm mentioned above in the discussion of the Pneuman & Kopp model. Taking results from all the loops and plotting β as a function of height gives the results shown in Figure 4. The results shown in this figure imply $\beta \to 1$ at a height of ~ 1.2 R_S even in active region loops. The numerous occurences of low cusp height seen by SXT/YOHKOH indicate that the results shown in Figure 4 are notunique and support the conclusion that $\beta > 1$ above ~ 1.2 R_S in streamers at all times during the solar cycle and not just near solar minimum or in idealized MHD models.

CONCLUSIONS

• $\beta > 1$ above ~ 1.2 R_S in streamers atall times during the solar cycle, even in the presence of active regions.

• Therefore, streamers are only weakly contained by internal magnetic fields. It is shown elsewhere (6, 12, 11) that the primary confinement is provided by the strong fields in adjacent coronal holes (where $\beta \ll 1$) pressing on the sides of the streamers.

ACKNOWLEDGMENTS

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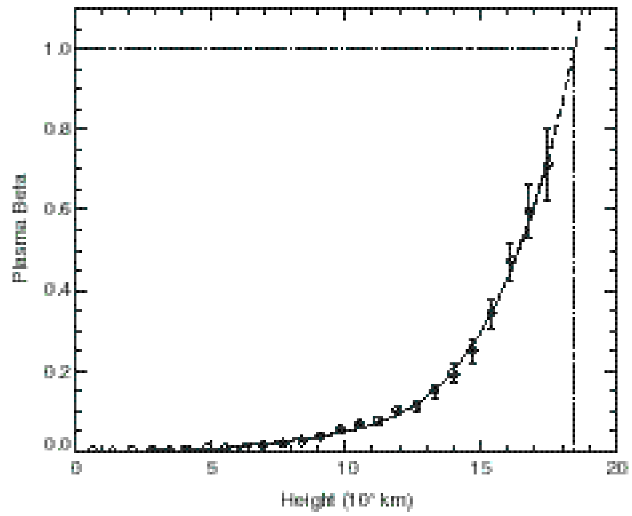

FIGURE 4. Plasma β for AR7999 on 26 November 1996 (4).

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